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SURVEY OF OPTICAL METHODS FOR THE DETERMINATION OF TEMPERATURES IN ROCKET ENGINES*

by

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SURVEY OF OPTICAL METHODS FOR THE DETERMINATION OF TEMPERATURES IN ROCKET ENGINES[1]

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A brief survey is presented of optical methods for the determination of temperatures in rocket engines. The data are presented in tables and include an outline of basic principles involved in application of a given technique, a sketch of the experimental arrangement, and key references which should be consulted for further details.

I. INTRODUCTION

Optical methods for the determination of temperatures have the unique advantage of permitting experimental observations without disturbing the system being studied. On the other hand, they usually involve averages over the field of view and are therefore incapable of yielding point functions for physical variables. Extensive applications of spectroscopic techniques have been made only to temperature measurements on laminar flames for premixed gases, although some studies have been reported also of temperatures, pressures, and velocities for rocket exhaust gases and for liquid- and solid-propellant combustion chambers.

Since review articles are available on the general subject of optical methods for measuring flame temperatures, a recent and extensive survey being one published by Penner in 1949(1), it does not appear to be necessary to emphasize historical development and to attempt a complete literature review.[2] Rather we shall content ourselves with

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[1] Supported by the ONR under Contract Nonr-220(03), NR 015-210.

[2] Numbers in parenthesis refer to the references listed at the end of the manuscript.

summarizing basic principles, with an outline of experimental arrangement, and with a set of key references denoted by (a) if referring to one of the earliest applications of the method, designated by (b) if containing an adequate review of basic principles and of some of the work done in the field, and identified by (c) if dealing with a recent example of good experimental technique. Many significant references have been omitted in this survey but those quoted should be sufficient to lead the interested reader to more extensive compilations of the literature. For a listing of references on jet propulsion research, a compendium published recently by the National Bureau of Standards may be consulted (2).

The subject of measurements of temperatures for isothermal and for non-isothermal emitters is surveyed in the following Sections II and III, respectively.

II. OPTICAL METHODS FOR MEASURING TEMPERATURES FOR ISOTHERMAL EMITTERS

From the operational point of view, there are as many different "temperatures" in flames as there are measuring techniques. However, experience has shown that the numerical values of a valid temperature determination approach, but never exceed, the adiabatic flame temperature provided measurements are made on quantities which are in equilibrium with the random translational energy distribution of the molecules. We may regard a value of the temperature determined under equilibrium conditions as a direct measure of combustion efficiency. In practice it may prove to be exceedingly difficult to eliminate all instances of non-equilibrium excitation. For this reason it is preferable to make temperature determinations by several independ-

ent methods rather than to assume that any one procedure leads to a significant approximation to the flame temperature. If two or more independent experimental techniques lead to the same numerical result, then it is very likely that the true flame temperature (defined through the random translational speed of the gas molecules) has been measured.

It is reasonable to consider that unequivocal experimental evidence of "temperatures" exceeding the adiabatic flame temperature indicates departures from equilibrium. If the existence of such abnormal "temperatures" can be established, valuable information may be obtained regarding some of the individual steps in the combustion processes. On the other hand, it is clear that the rocket engineer performing a temperature measurement in order to learn something about the average state of combustion or about the combustion efficiency, will be interested in experimental procedures which measure the average combustion efficiency rather than non-equilibrium distributions of an excited chemical species whose role in the combustion reactions may be only of academic significance.

A summary of optical methods for measuring temperatures of isothermal emitters is given in Table I. The remarks at the end of each section contain recommendations relating to the use of the method, and are based on the results of available practical experience. The symbols are identified in the summary on nomenclature appended to the report.

Table I. Optical Methods for the Determination of Temperatures of Isothermal Radiators.

1. DETERMINATION OF BRIGHTNESS TEMPERATURES

Principles

The brightness temperature T_{br} at the wavelength λ is defined[3] as the temperature at which the emitter under study emits the same spectral intensity of radiation as a blackbody. Thus $c_1\lambda^{-5}\left[\exp(c_2/\lambda T_{br}) - 1\right]^{-1} =$ measured intensity at λ. The brightness temperature T_{br} is related to the actual temperature T_F, of the emitter by the relation

$$(1/T_F) - (1/T_{br}) = (\lambda/c_2)\ln \varepsilon_\lambda \qquad [1]$$

provided an average emissivity ε_λ can be assigned to the emitter for the wavelength region to which the pyrometer responds.

Experimental Procedure

An optical pyrometer is suitable for measuring the brightness temperatures of flames. The wavelength region is selected by a filter. A pyrometer compares the brightness of the source with that of a tungsten filament heated to a known temperature.

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[3] The phrase "at the wavelength λ" is used to summarize the statement "in the wavelength region between λ and $\lambda + \Delta\lambda$" where $\Delta\lambda$ is generally a wide wavelength interval (i.e., of the order of 100Å). For methods 1 to 5 it is advantageous to use a spectroscopic instrument of low resolving power, i.e., to utilize average emissivities over wide wavelength regions. In this case the observations will not be affected significantly by discrete lines.

Table I. (Continued).

Remarks

A measurement of the brightness temperature T_{br} can oe used to obtain the temperature T only if the spectral emissivity ε_λ is known, which is generally not the case. For flames containing solid particles (such as finely divided carbon) the emissivity ε_λ may be known or else may not differ greatly from unity. The method is not useful for reacting gas mixtures.

References

(a): (3).

(b): (1).

(c): Manuals supplied with commercial optical pyrometers.

2. TWO-COLOR TEMPERATURES

Principles

The color temperature T_c of an emitter is defined as the temperature at which a blackbody emits radiation having the same ratio of radiant intensities at the wavelengths λ_1 and λ_2 as the emitter under study. This definition of T_c is expressed by the relation

$$J(\lambda_1, T_c)/J(\lambda_2, T_c) = \varepsilon_{\lambda 1}(\lambda_1, T)J(\lambda_1, T)/\varepsilon_{\lambda 2}(\lambda_2, T)J(\lambda_2, T) \qquad [2]$$

The color temperature T_c is related to the true temperature T through the expression

Table I. (Continued).

$$(1/T) - (1/T_c) = \ln(\varepsilon_{\lambda 1}/\varepsilon_{\lambda 2})/c_2\left[(1/\lambda_1) - (1/\lambda_2)\right] \quad [3]$$

if the intensity of radiation emitted by a blackbody may be approximated by Wien's equation, i.e., if $\lambda T \ll c_2$.

Experimental Procedure

The two-color method requires the determination of intensity ratios in emission at two wavelengths. Photoelectric detectors with wavelength filters are useful receivers.

Remarks

The two-color method can be used if emissivity ratios at two wavelengths are known. For flames containing solid particles it may be possible to calculate or measure emissivity ratios (4,5) or else it may be justified to assume that the emitter is a greybody, i.e., $\varepsilon_{\lambda 1} = \varepsilon_{\lambda 2} < 1$.

For homogeneous gases at elevated pressures the two-color method can be made precise by selecting wavelength regions for which emissivity ratios can be calculated as a function of temperature and pressure. The labor involved in the use of the precise procedure is considerable and no published examples of application are available.

References

(a): (4).

(b): (1), (5), (6).

(c): (5), (6).

Table I. (Continued).

3. LINE-REVERSAL TEMPERATURES

Principles

A thermally excited spectral line may be studied by use of a spectroscope. If the background is not as bright as the flame in a wavelength region including the line center of the emission line, then a bright emission line is observed. On the other hand, if the background is brighter than the flame, the line will appear as a dark absorption line. For a background of arbitrary emission characteristics the emission line merges with the background ("point of reversal") when

$$T_F = T_{Sbr} \qquad [4]$$

where the subscripts F and Sbr identify the true temperature of the flame and the brightness temperature of the background, respectively. It is noteworthy that Equation [4] holds for arbitrary emissivities of the flame.

Experimental Procedure

Some of the earliest applications of the reversal method were made to infrared emission bands of H_2O and CO_2, which are normally present in hydrocarbon flames (7, 8). If it is desired to make observations in the visible region of the spectrum, it is necessary to color non-luminous flames by addition, for instance, of sodium salts, which will emit the yellow "D" lines of sodium.

The experimental arrangement is sketched in Figure 1. A small direct-vision spectroscope is suitable for reversal experiments on the

Table I. (Continued).

sodium D-lines. The brightness temperature of the background is measured with an optical pyrometer.

Remarks

The method depends on the assumption that the spectral line on which observations are made is excited thermally. This is not necessarily the case. For example, temperatures greatly in excess of the adiabatic flame temperatures have been reported by Gaydon and Wolfhard (9) for the reversal temperatures of iron lines in low-pressure flames. In general, however, the sodium line-reversal method is one of the most convenient and useful methods for temperature determinations in regions of active combustion.

The reversal technique can be extended to cover the case in which the temperature is obtained without requiring precise determination of the point of reversal. This extension has been carried through in the infra-red by Silverman(10) and for the OH bands in the ultraviolet by Curcio, Stewart, and Petty (11).

References

(a): (7), (8), (12).

(b): (1,), (9), (13).

(c): (9), (10), (13).

Table I. (Continued)

4. THE TWO-PATH METHOD

Principles and Experimental Procedure

For a two-path experiment in which the intensities of radiation for a single traversal and for two traversals are measured, let T_{br_1} and T_{br_2} be the corresponding brightness temperatures and R_λ the reflectivity of the mirror at the wavelength λ. The true temperature of the flame T_F is then given by the expression

$$1 - \exp\left\{(-c_2/\lambda)\left[(1/T_{br_2})-(1/T_{br_1})\right]\right\} = -R_\lambda\left\{1 - \exp(-c_2/\lambda)\left[(1/T_{br_1})-(1/T_F)\right]\right\} \quad [5]$$

if $\lambda T \ll c_2$.

The two-path method is essentially a reversal method in which the source is used as its own background. Two observations of brightness are made, one with a cool blackbody behind the flame and another with a mirror behind the flame.

Remarks

The two-path method for the measurement of flame temperatures is an optical technique which permits temperature measurements on systems in which the intensity of radiation emitted varies rapidly (and aperiodically) with time. The method is recommended for use whenever spectral emissity data are not available, i.e., for practically all radiators. This method involves the implicit assumption that the emissivity

Table I. (Continued)

is a slowly-varying function of the wavelength in the spectral region at which measurements are made. This assumption becomes apparent if we note that the derivation of Equation [5] involves the use of an average emissivity over the spectral region to which the instrument responds. It is known from experimental studies that the two-path method usually constitutes a very useful experimental procedure for studying the progress of combustion in liquid- and solid-propellant rocket chambers (14).

References

(b): (1), (14).

(c): (14).

5. COMPENSATED HOT-WIRE METHOD

Principles and Experimental Procedure

The temperature of a tungsten wire heated in a vacuum, as determined by an optical pyrometer, will be a function of the power input and consequently of the heating current I (Cf. curve 1 in Figure 2). Suppose this wire is placed in a flame of temperature T_F. When the temperature of the wire is below T_F, the wire will be heated by conduction from the hot gases. Therefore, less current will be required to maintain a given temperature in the flame. Above T_F more current is required than in a vacuum in order to maintain a given wire temperature since heat is now lost by conduction to the flame. A plot

Table I. (Continued)

of T vs I for a wire in a flame gives curve 2 of Figure 1 which intersects curve 1 at $T = T_F$. At $T = T_F$ there is not heat exchange between the wire and the flame.

Remarks

The method involves the assumption that the wire does not disturb the combustion processes and that its emissivity in the flame is the same as in a vacuum. Although numerous examples of catalytic action by wires in flames have been observed, the compensated hot-wire method is simpler to use than conventional thermocouples and hence is recommended for studies on flames in which point by point explorations are desired.

References

(a): (15).

(b): (1), (13), (15).

(c): (15).

6. POPULATION (ROTATIONAL, VIBRATIONAL, AND ELECTRONIC) TEMPERATURES

Principles

The rotational, vibrational and electronic temperatures are defined through the populations of molecules in different rotational, vibrational, and electronic energy levels. Hence it is appropriate to refer to them collectively as population temperatures.

The intensity of a spectral line depends on the population of the initial state involved in a transition and also on the transition probability.

Table I. (Continued)

If the energy levels of the initial states are populated in accord with the Boltzmann distribution law, then the intensity of absorption lines, I_{abs}, and of emission lines, I_{em}, are given by equations of the form:

$$I_{abs} = \alpha_1 i_1 \nu_1 \exp(-\epsilon_1 / kT_1) \quad [6]$$

$$I_{em} = \alpha_2 i_2 \nu_2^4 \exp(-\epsilon_2 / kT_2) \quad [7]$$

where α_1 and α_2 are known quantities for given transitions, i_1 and i_2 are the transition probabilities, ν_1 and ν_2 are the frequencies of the line centers, and ϵ_1 and ϵ_2 are the energies of the initial levels involved in absorption and in emission experiments, respectively. In first approximation the energies ϵ can be represented as the sum of rotational (ϵ_{rot}), vibrational (ϵ_{vib}), and electronic energy levels (ϵ_{el}). From Equations [6] and [7] it can be shown that

$$-\partial \ln(I_{abs}/i_1\nu_1)/\partial \epsilon_{1,i} = (kT_{1,i})^{-1} \quad [8]$$

and

$$-\partial \ln(I_{em}/i_2\nu_2^4)/\partial \epsilon_{2,i} = (kT_{2,i})^{-1} \quad [9]$$

where the subscript i may represent either rot, vib, or el. It should be noted that the population temperatures in absorption ($T_{1,i}$) and in emission ($T_{2,i}$) may be different for a given chemical species.

Table I. (Continued)

Experimental Procedure

Well-resolved spectra showing individual spectral lines are, in general, required. In order to minimize temperature gradients normal to the direction of observation, low-pressure flames have been used, particularly by Gaydon and Wolfhard (16, 17).

Remarks

Determination of population temperatures requires elaborate apparatus and has been used most widely for premixed gases and for diffusion flames (18). This method is of primary importance for studies designed to determine combustion mechanism. There has been considerable discussion recently concerning the proper interpretation of experimental data obtained for OH (19-23).

References

(a): (24).

(b): (19), (20), (23), (25).

(c): (16), (17), (26).

7. TEMPERATURE MEASUREMENTS UTILIZING SPECTRAL LINE-SHAPE

Principles

The mean translational temperature of individual chemical species can be obtained from a study of spectral line-shape. For example, for spectral lines with Doppler-contour the half-width $\Delta\lambda_D$ (i.e., one half of the width of the spectral line for which the spectral absorption coefficient exceeds one half of its maximum value) is related

Table I. (Continued)

to the temperature, T_F, defined by the random translational motion through the relation

$$\Delta\lambda_D = (\ell n\ 2)^{(1/2)}(2\ kT_F/mc^2)^{(1/2)}\lambda_o \qquad [10]$$

where m is the known mass of the molecule under study and λ_o is the wavelength at the line center.

Experimental Procedure

Methods utilizing detailed spectral line shapes require the use of very high-resolution instruments such as interferometers and echelette gratings.

Remarks

The interpretation of experimental data is greatly complicated by the inevitable temperature gradients present in all flames. The method holds the greatest promise for low-pressure flames in which the spectral line-shape is relatively simple. Two-path experiments in the infrared and in the ultraviolet have been proposed recently for the simultaneous determination of temperatures and concentrations.

References

(a): (27).

(b): (20), (27).

(c): (27).

III. OPTICAL METHODS FOR MEASURING TEMPERATURES FOR NON-ISOTHERMAL EMITTERS

It is impossible to measure flame temperatures in non-isothermal systems by optical methods unless either (a) the temperature gradients

are known or (b) the non-isothermal system can be approximated by two or more adjacent isothermal regions. The few published flame temperature measurements, in which attempts were made to correct for temperature gradients, all involve the use of simple flame models. A summary of published data is presented in Table II.

Table II. Optical Methods for the Determination of Temperatures of Non-Isothermal Radiators.

1. REVERSAL TEMPERATURES FOR NON-ISOTHERMAL EMITTERS

Principles and Experimental Procedure

Griffith and Awberry(28) showed that the observed reversal temperature was approximately that of the hot region if light from the reversal background passed first through a cool zone and then through a hot zone. If the hot and cold regions were interchanged then intermediate temperatures were observed.

Remarks

The conclusions reached by Griffith and Awberry(28) are applicable only to the system on which observations were made and cannot be generalized to other flames.

References

(a): (28).

(b): (1), (13), (28).

(c): (28).

Table II. (Continued)

2. REVERSAL TEMPERATURES UTILIZING MEASUREMENTS OF SPECTRAL LINE-SHAPE

Principles

Strong, Bundy, and Larson[29] have used an interferometer to study line-reversal in non-isothermal systems. They obtained resolving power sufficient to observe the contour of individual spectral lines. Analysis of the experimental data involves the assumption that the non-isothermal system can be described by two adjacent isothermal regions.

In a flame the observed line-width is determined by three factors, viz., Doppler broadening, collision broadening, and "absorption-broadening" which depends on the concentrations of sodium in the hot and cold regions. In an emission experiment the resultant line-contour may have the shapes illustrated in Figures 3a and 3b. If the line shown in Figure 3b is studied in a reversal experiment with a high resolution spectrograph, reversal is observed in different regions of the line as the brightness of the background is increased. For a suitable source the central region of the line absorbs light and appears dark whereas the wings of the line remain brighter than the source, thus producing the contour shown in Figure 3c.

Strong, Bundy, and Larson suggested that, under low resolution, total reversal would be observed when the sum of the areas A and A' is equal to the area B (Cf. Figure 3c). The authors calculated the contours of Na lines for various optical densities in the hot and cold zones. These were

Table II. (Continued)

combined to give the observable contour from which the aparent reversal temperature could be derived. The calculations checked well with the observed reversal temperatures for the two zones whose reversal temperatures and optical densities had been determined separately.

The decomposition of an experimentally determined line contour of the type shown in Figure 3c to yield separate temperatures for the hot and cold regions has not been described. This inversion can probably not be performed uniquely.

Experimental Procedure

The experiments carried out by Strong, Bundy, and Larson utilized a Fabry-Perot interferometer in order to obtain line contours. The apparatus was elaborate and costly. The work is of particular interest in the present context because it was extended (30) to measurements of the velocities and pressures of rocket exhaust gases.

3. POPULATION TEMPERATURES

Principles

For flames represented by two adjacent isothermal regions, it is possible to carry through a complete analysis for observable intensities of individual spectral lines (23, 31). Applications of the results to flames have not yet been published.

NOMENCLATURE

α_1 , α_2	=	known proportionality constants.
c_1	=	first radiation constant = 3.74×10^{-5} (erg-cm^2)/sec.
c_2	=	second radiation constant = 1.432 cm-$^{\circ}$K.
c	=	velocity of light.
$\mathcal{E}$	=	total energy of initial quantum state.
$\mathcal{E}_{e\ell}$	=	electronic energy of initial quantum state.
$\mathcal{E}_{rot}$	=	rotational energy of initial quantum state.
$\mathcal{E}_{vib}$	=	vibrational energy of initial quantum state.
$\mathcal{E}_\lambda$	=	average emissivity for the wavelength range between λ and $\lambda + \Delta\lambda$.
I	=	total intensity of a spectral line.
i	=	transition probability.
$J(\lambda, T)$	=	radiant intensity emitted by a blackbody at wavelength λ and temperature T.
k	=	Boltzmann constant.
λ	=	wavelength.
m	=	mass of a molecule.
ν	=	frequency.
R_λ	=	average reflectivity for the wavelength range between λ and $\lambda + \Delta\lambda$.
T	=	absolute temperature.
T_F	=	flame temperature.
T_{br}	=	brightness temperature of a flame.
T_{Sbr}	=	brightness temperature of the light source used in reversal experiments.
T_c	=	color temperature of a flame.

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LIST OF FIGURES

FIGURE 1. EXPERIMENTAL ARRANGEMENT FOR LINE-REVERSAL MEASUREMENTS (SCHEMATIC). THE SPECTROSCOPE IMAGES ARE REPRESENTATIVE OF RESULTS OBTAINED FOR THE D-LINES OF SODIUM.

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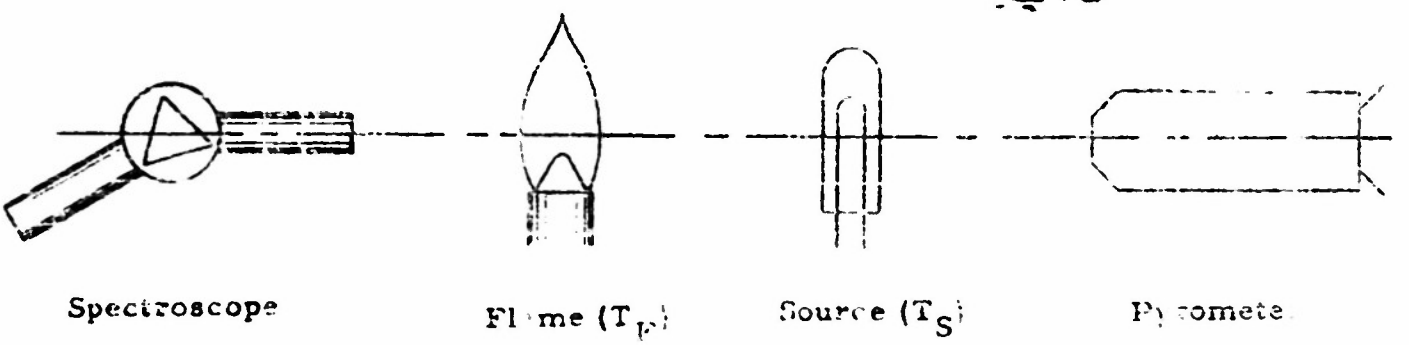
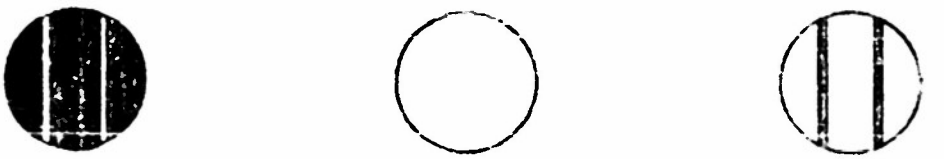
(c) REVERSAL EXPERIMENT. ABOVE THE HORIZONTAL LINE THE EMITTED INTENSITY EXCEEDS THE INTENSITY OF THE REVERSAL BACKGROUND: BELOW THE HORIZONTAL LINE THE CONVERSE APPLIES.



Experimental Arrangement (Schematic)



Images Formed in Spectroscope

Figure 1. Experimental arrangement for line-reversal measurements (Schematic). The spectroscope images are representative of results obtained for the D-lines of sodium.

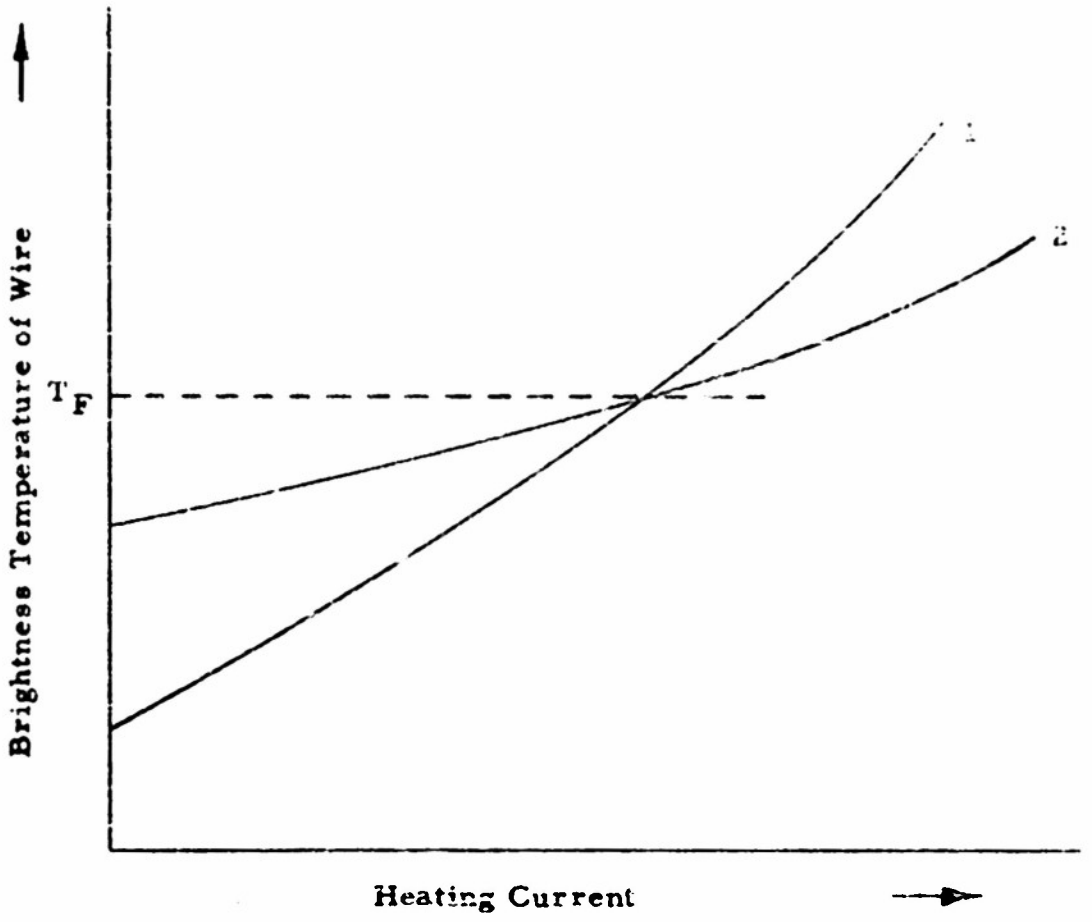
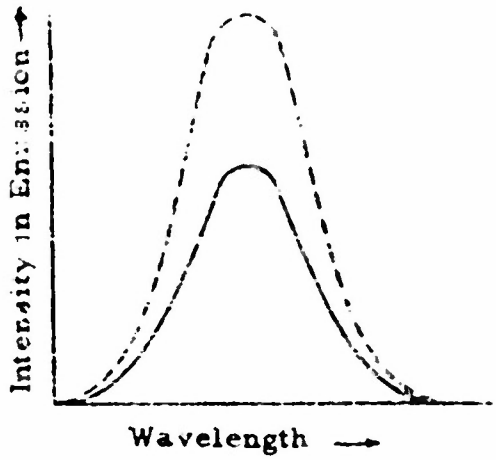
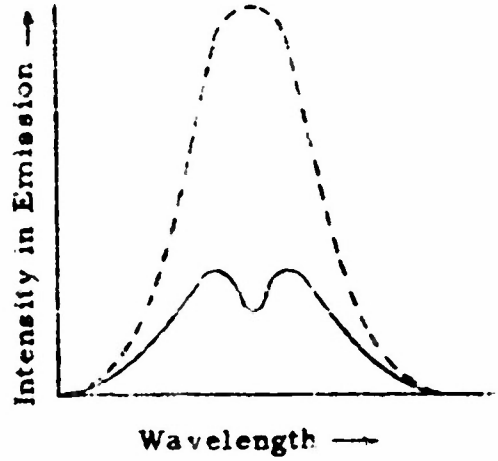


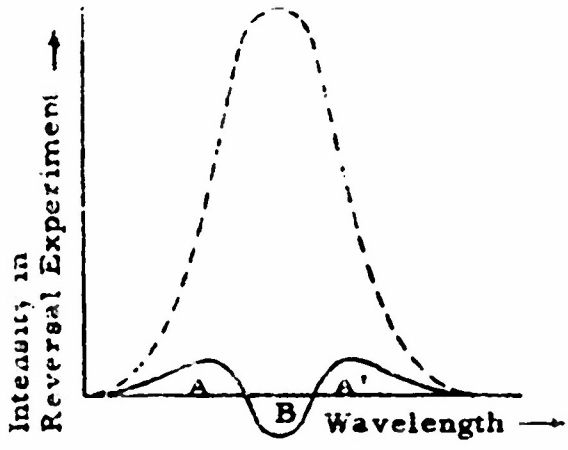
Figure 2. Plot of heating current vs. temperature for compensated hot wire method. Curve 1 applies for a wire in vacuum, curve 2 applies for the wire in a flame.



(a) **Emission experiment.** The dotted curve represents the emission which would be observed from the hot region alone. **The solid curve is produced as the result of absorption of radiation by the cool gas layer.**



(b) **Emission experiment.** The optical density in the cool gas layer has been increased to the point where self-reversal occurs.



(c) **Reversal experiment.** Above the horizontal line the emitted intensity exceeds the intensity of the reversal background; below the horizontal line the converse applies.

Figure 3. Contours of spectral lines obtained when a hot isothermal region is viewed through a cool isothermal gas layer (schematic)

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